

ART. II.—*The Pakenham Meteorite.*

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INTRODUCTION.

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Introduction.

The Pakenham meteorite was found during the widening of the Princes Highway in 1928, at a point 3 miles west of Pakenham township, in the Parish of Berwick, County of Mornington. It was discovered in soil at a depth of 3 feet, and was collected by an officer of the Country Roads Board. A small fragment, weighing only a few ounces, and now lost, was knocked off one corner and sent to the Mines Department of Victoria for identification. Subsequently the meteorite was obtained for the Mines Department by Mr. D. J. Mahony, then Government Petrologist, and lodged in the Geological Survey Museum in February, 1929. The meteorite was coated with limonite scale when found, and weighed 89 lb. It continued to rust and scale in the Museum, and in December, 1936, this had reduced its weight to 71 lb., a loss of 18 lb. in nearly eight years.

This meteorite closely resembles both in chemical and mineralogical composition the other masses of meteoritic iron found in this part of Victoria, namely, the Cranbourne, Beaconsfield, and Langwarrin meteorites. Walcott (8) has shown that the localities from which these several meteorites were obtained lie more or less on a straight line, suggesting that they were all derived from the breaking up of a single large iron meteorite during flight. The location of the Pakenham meteorite also conforms to this line, and it was probably derived from the same source.

Hodge-Smith (3) records the occurrence of an undescribed iron meteorite from what is apparently the same locality as that of the Pakenham meteorite, under the name of "Cranbourne No. 6". He records the weight of this "Cranbourne No. 6" as 9.0 kg. (20 lb.), and states that it was secured by Mr. D. J. Mahony in

1928, and lodged in the National Museum, Melbourne. It would appear that the Pakenham meteorite and the "Cranbourne No. 6" might be one and the same, but it seems that Hodge-Smith's record is incorrect. There is no meteorite corresponding to the "Cranbourne No. 6" in the collection of the National Museum, nor was a piece of iron weighing 20 lb. removed from the Pakenham meteorite; and this is borne out by the appearance of the meteorite. While the meteorite under discussion may well be the "Cranbourne No. 6" of Hodge-Smith, we propose to avoid confusion by naming it after the locality in which it was found.

Description of the Meteorite.

When submitted to us for examination, the Pakenham meteorite was roughly ellipsoidal in shape, measuring 12 in. \times 7.5 in. \times 6.5 in., and was coated with limonite scale. As in most of the Cranbourne meteorites, any original surface features have been completely destroyed by scaling and rusting. Its weight, as received, was 65 lb. (December, 1940), representing a further loss in weight of 6 lb. between December, 1936, and December, 1940.

Nodules.

With the meteorite came several nodules which had been recovered from time to time from the scale falling from it during its sojourn in the Geological Survey Museum; and similar nodules were discovered when de-scaling the iron to slice it. These nodules resemble those found in the other Cranbourne meteorites. They are generally ellipsoidal in shape, but one was pear-shaped. They consist of a core of pyrrhotite, sometimes enclosed by a zone rich in graphite, and surrounded by a narrow rim of iron-nickel phosphides (Fig. 2). A thin band of limonite generally occurs between the phosphide rim and the sulphide core, and veinlets of limonite have invaded the sulphides. The largest nodule found (Fig. 2) measured 40 mm. \times 30 mm. \times 21 mm., and weighed 45 grams. It had a specific gravity of only 3.643, while smaller nodules had specific gravities of the order of 4.5-4.7. The low value of the large nodule is due to the presence of abundant graphite in it.

Preparation of the Specimen for Examination.

The meteorite was first de-scaled with a cold chisel and a hammer; about 5 lb. of scale were removed and kept for examination. It was then taken to the Metallurgy School, University of Melbourne, and cut with an oxy-acetylene flame by Mr. A. Wilcock. The meteorite and the piece cut from it were cooled first in a stream of compressed air, and then in a bath of water. Flat surfaces were obtained by treating both pieces in a shaping machine, in which all the fused material was removed, as well as a considerable further thickness to ensure the elimination

of any heat effect on the structure of the iron. Tool marks were removed by subsequent grinding with various grades of carborundum, and a final polish was obtained on a buffing machine. During the shaping process it was noted that the marginal portion of the iron was harder than the centre. A mirror-like polish was obtained, but rusting developed on the surface within 48 hours. The surface was then re-polished, etched with 2 per cent. nitric acid in alcohol to bring out the octahedral structure, and treated to preserve it from further rusting. No pyrrhotite nodules were encountered either during the cutting or the shaping.

After these operations the main mass of the meteorite weighed 56.5 lb. This is now in the Geological Survey Museum (No. 8150). Several small pieces weighing altogether 4 oz. were sawn off the piece that had been removed, and polished for mineralogical examination. These and the polished remainder of the slice, weighing 1 lb. 4.5 oz., are lodged in the Melbourne University Geological Museum.

Widmanstätten Structure.

Etching of the two large polished surfaces with 2 per cent. nitric acid in alcohol brought out pronounced Widmanstätten figures (Fig. 1). The width of the lamellae of kamacite forming this structure varied from 1 mm. to 7 mm., and the average of 41 measurements was 3 mm. On this basis the Pakenham meteorite may be described as a coarse octahedrite, and falls into the group (Og) of Prior's classification (5).

Specific Gravity.

The specific gravity of the large slice removed from the end of the meteorite is 7.20, that of the smaller pieces sawn from this 7.032, and that of a selected sample of fresh, clean shavings collected during the final shaping treatment 7.927. The value obtained from the shavings is probably the more accurate measurement for the actual iron, since the shavings were free from cracks and nodules. The lower figures for the larger pieces may be put down to the presence of air films in cracks and possibly the presence of nodules of pyrrhotite.

Chemical Analysis.

A chemical analysis (Table 1., Column No. 1) was made from a sample of 2.5 gm. of fresh, clean shavings obtained during the final stage of shaping the meteorite.

The sample was not wholly representative of the meteorite, since it contained neither sulphur nor carbon, although both these elements are present in the nodules of the meteorite as pyrrhotite and graphite. No determination was made for chlorine, but this element was also proved to be present during the mineralogical examination. Disregarding these inadequacies, however, it will be seen that the Pakenham meteorite closely resembles the

Cranbourne No. 2, and is not greatly different from the other irons from this district. It also indicates that the Pakenham meteorite belongs to the nickel-poor, coarse octahedrite group.

TABLE 1.

—					1	2	3	4	5
Fe	..	..	..	..	92.31	91.08	92.34	92.56	92.28
Ni	..	..	..	..	6.81	8.11	6.38	7.34	6.24
Co	..	..	..	..	0.54	0.50	0.75	0.48	0.58
Cu	..	..	..	..	nil	0.01	0.02	0.02	0.06
P	..	..	..	..	0.37	0.11	0.19	0.26	0.17
S	..	..	..	..	nil	..	0.18	0.04	..
C	..	..	..	..	n.d.	..	..	0.05	..
Cl	..	..	..	..	n.d.	..	..	0.01	..
Insoluble	..	..	..	..	nil	0.17	..	..	0.32
Totals	..	..	..	..	100.03	99.98	99.86	100.76	99.65
Fe : Ni	..	..	..	..	13.5	11.2	14.5	12.6	14.8
Sp. Gr.	..	..	..	..	7.93	7.46	..	..	..

1. Pakenham meteorite, anal.—A. B. Edwards.
2. Cranbourne No. 1, anal.—W. Flight (2).
3. Cranbourne No. 2, anal.—P. G. W. Bailey and A. G. Hall (8).
4. Beaconsfield, anal.—O. Siostrom (8).
5. Langwarrin, anal.—P. G. W. Bailey and A. G. Hall (8).

Mineral Composition.

Microscopical examination of polished sections of the nickel-iron and of the nodules reveals that the iron is composed chiefly of kamacite (α -nickel-iron), with minor amounts of taenite (γ -nickel-iron), and various phosphides. The nodules consist of pyrrhotite and graphite, the pyrrhotite forming the core, enclosed by a narrow rim of iron-nickel phosphides, with an inner margin of limonite. In addition, minute parallel strings of a grey-white mineral, possibly, daubrechite, were observed in the pyrrhotite. The oxidized crust or scale of the meteorite consists chiefly of limonite with residual patches of nickel-iron and the phosphides. In places, trevorite is associated with it, and some of the scales are encrusted with small quantities of the chlorides of iron and nickel.

Kamacite (α -nickel-iron) is iron-white and isotropic, strongly magnetic, and readily scratched with a steel needle. Standard etching reagents behave as follows:— HNO_3 produces an immediate etching, but without effervescence; HCl fumes tarnish, and the iron washes and rubs brown, but the effect is not consistent; KOH and KCN are negative; FeCl_3 instantly turns the iron brown, bringing up grain boundaries, and etching grains differentially, as well as bringing up a few Neumann lines; HgCl_2 darkens the surface immediately. Of the other etching reagents tried, 2 per cent. picric acid in alcohol and bromine water both attack the kamacite, darkening it, and bringing up grain boundaries and crystal structure by differential etching.

Taenite (γ -nickel-iron) is present only as occasional groups of parallel lamellae between plates of kamacite (Plate III., figs. 5 and 6), and as small triangular areas in the interstices of kamacite grains. The taenite occurs in the dark bands that outline the Widmanstätten structure (Plate II., fig. 1). The appearance of the etched specimen is misleading, however, in that it gives the impression that the dark bands are broad and uniform. Actually the dark bands consist of closely interleaved narrow lamellae of taenite and kamacite (Plate III., fig. 5).

The taenite is scarcely distinguishable from the kamacite in unetched sections, but is readily distinguished after etching with picric acid, bromine water, or 2 per cent. HNO_3 in alcohol, all of which darken the kamacite, but do not affect the taenite. Standard etching reagents behaved as follows:— HNO_3 , KOH , KCN , FeCl_3 , HgCl_2 were all negative; HCl fumes tarnished the taenite a deeper brown than they did the kamacite, but the results were not consistent. The taenite is strongly magnetic, isotropic, and is readily scratched with a steel needle.

Where the taenite forms triangular areas at the junction of several crystals of kamacite, it commonly forms a fine-grained ex-solution intergrowth with the kamacite. The kamacite occurs as minute ex-solution bodies of lens-like form, with their long axes parallel to one or other of three directions. This structure is closely comparable with that observed in the Tawallah Valley meteoric iron (1). The transformation of γ -nickel-iron (taenite) into α -nickel-iron (kamacite) as indicated in this connection is accompanied by a gradual enrichment of the residual γ -nickel-iron in nickel. This has the effect of depressing the temperature of transformation, and finally the residual γ -nickel-iron becomes so enriched in nickel that the temperature of transformation is depressed too low for the change to continue. The alloy then becomes stable as a mixture of α -nickel-iron and γ -nickel-iron, the proportion of the two constituents depending on the composition of the original γ -nickel-iron. Further, it was shown that the transformation proceeds by the development of small bodies of α -nickel-iron in the octahedral directions of the original γ -nickel-iron, and that as the transformation progresses these bodies grow in size by solid diffusion, forming oriented lamellae, and forcing residual γ -nickel-iron to take up its position interleaved between these lamellae. Thus arises the Widmanstätten structure. The Tawallah Valley iron was of such a composition that this transformation was unable to progress beyond the stage when small oriented ex-solution bodies of α -nickel-iron had developed in the base of γ -nickel-iron. The nickel content of the Pakenham meteorite, on the other hand, is such that the transformation went almost to completion; and it was only checked when a minute amount of nickel-rich γ -nickel-iron remained. The very thin lamellae of this residual γ -nickel-iron appear homogeneous, but the slightly larger triangular areas reveal the ex-solution structure by which the transformation was accomplished.

Pyrrhotite has been observed only in the cores of nodules picked out from the weathered parts of the meteorite. It has a creamy-brown colour, is strongly anisotropic and pleochroic, and strongly magnetic. In some nodules it forms innumerable minute interlocking grains, while in others it occurs as two or three coarse grains. In still others, patches of coarse-grained pyrrhotite interdigitate with patches of finer-grain. It is readily distinguished from troilite by its etching reactions. Thus HNO_3 tarnishes the surface, but washes clean, whereas with troilite it causes vigorous effervescence and the evolution of H_2S . Again HCl fumes tarnish the surface of the pyrrhotite, but do not otherwise affect it, whereas troilite effervesces vigorously with HCl and is stained brown. Of the other reagents, KCN , FeCl_3 , and HgCl_2 are negative, while KOH slowly stains the surface brown, and reveals the presence in the pyrrhotite of parallel strings of grey inclusions (Plate III., fig. 8). Microchemical tests indicate that it is not nickeliferous.

The pyrrhotite may form the whole of the nodule core, when it is enclosed by a thin rim of iron-nickel phosphides from which it is separated by a narrow zone of limonite; or it may occur as an irregular-shaped core, surrounded by a zone of pyrrhotite intergrown with graphite (Plate II., fig. 2). The proportion of graphite tends to be greater near the outer edge of the nodule, where it gives place to a zone of clear pyrrhotite, enclosed in turn by a narrow rim of phosphides and limonite.

Graphite was also found as occasional flakes in part of the limonitic coating of the meteorite. In polished sections it is a brownish-grey colour, showing distinct anisotropism and pleochroism. It is soft, brittle, inert to all etching reagents, and marks paper.

(?) *Daubreelite*.—The blebs of grey mineral occurring as small parallel strings in the pyrrhotite (Plate III., fig. 6) are thought to be the rare chromium sulphide daubreelite. This mineral has been recorded from the Cranbourne No. 1 meteorite by Flight (2) and Smith (6), where it formed zones about the troilite in troilite nodules, and from the Langwarrin meteorite by Walcott (8), who regarded "extremely fine veins traversing the thick vein of troilite" which was exposed in the polished face of this meteorite as daubreelite because an analysis of the troilite revealed a trace of chromium.

The mineral in the Pakenham meteorite is isotropic and inert to all etching reagents; and is harder than the enclosing pyrrhotite. The individual blebs forming the strings are too small, however, to test microchemically. The orientation of the strings is parallel to a crystallographic direction of the pyrrhotite, and the direction of the strings varies from grain to grain of pyrrhotite.

Iron-nickel Phosphides.—Four varieties of iron-nickel phosphide have been observed in the meteorite. Of these two occur as rims around pyrrhotite nodules, and always associated together.

The other two occur in the nickel-iron, and do not appear in the nodules. Of the two forming the rims about the nodules, one is identified as schreibersite, while the other corresponds to the brassy coloured phosphide recorded from the Cranbourne No. 1 meteorite. Of the two in the iron, one has been identified as rhabdite, while the other is probably a variety of schreibersite, of somewhat different composition to that in the nodule rims. It is referred to here as "schreibersite B". All four show distinctive features in their appearance, and particularly in their behaviour to standard etching reagents, as set out in Table 2.

TABLE 2.
ETCHING BEHAVIOUR OF PHOSPHIDES.

	HNO ₃	HCl	KCN	FeCl ₃	HgCl ₂	KOH
Rhabdite
Schreibersite. .	+	+
Schreibersite B	+
Yellow phosphide	+	..

Rhabdite.—This occurs as small rhombs and prisms scattered throughout the massive kamacite (Plate III., figs. 2, 3) in a manner and form identical with the descriptions of rhabdite cited by Walcott (8) and figured by Johnston and Ellsworth (4). It is much harder than the enclosing iron and cannot be scratched with a steel needle. It is brittle and brown by contrast with the iron, strongly magnetic, and distinctly anisotropic. Tests on a small amount of powder composed of such rhombs, and obtained as the insoluble residue from 50 grams of iron which had been dissolved in 1:1 HNO₃, gave tests for iron, nickel, and phosphorus.

Schreibersite.—This is a tin-white, brittle, hard mineral which cannot be scratched with a steel needle, occurring as the outer rims to the pyrrhotite nodules (Plate III., fig. 7). It is difficult to polish owing to its brittle nature, and is distinctly anisotropic, and strongly magnetic. Tests on fragments gave positive tests for iron, nickel, and phosphorus. When etched with HNO₃ it effervesces very slowly, the bubbles rising from the numerous cracks that traverse the surface. On treatment with KOH it tends to develop a brown stain, which washes brown, and rubs pale brown. This action is a very slow one, and may take place only after several minutes. Sometimes it takes place with a single application of KOH, sometimes only after two or three applications to the same spot.

Yellow Phosphide.—Associated with the schreibersite, but subordinate to it, is a creamy yellow material (Plate III., fig. 7).

This is softer than the schreibersite, being readily scratched with a needle, and lacks the brittleness of the schreibersite. Moreover, it does not appear to be magnetic, and is isotropic. Powder excavated from a large crystal gave positive tests for iron, nickel, and phosphorus, the nickel test being particularly strong. The mineral is negative to all the etching reagents but HgCl_2 . With HgCl_2 it is slowly stained brown to purplish brown. The stain washes the same colour and is difficult to rub off, when it leaves a slightly roughened surface.

Schreibersite B.—The fourth phosphide occurs as occasional large, irregular areas whose shapes are partially controlled by the octahedral structure of the iron (Plate II., fig. 1), but generally as vein-like areas in the interstices of the α -nickel-iron crystals (kamacite crystals), and is extremely difficult to polish on account of its brittleness (Plate III., fig. 6). It is weakly anisotropic, and in hardness, brittleness, magnetic property, and general appearance, it resembles schreibersite. In colour, however, it is almost identical with the rhabdite crystals in the adjacent iron crystals, while, in etching properties, it is distinct from both. Unlike schreibersite, it is negative to both HNO_3 and KOH , but with HCl it effervesces slowly, the bubbles rising from the numerous cracks; and this latter behaviour distinguishes it from the rhabdite, which is negative to HCl . Tests on minute fragments broken from a vein with a micro-drill gave tests for iron, nickel, and phosphorus.

Walcott (8) described material of similar occurrence in the related Cranbourne No. 2 meteorite as schreibersite, but with the remark that "it differs seriously in composition from that usually ascribed to schreibersite".

The chemical analyses of the various phosphides found in the related Cranbourne and Beaconsfield meteorites (8) are summarized in Table 3, and show that the chief variant is the Ni/Fe ratio, the proportion of Ni ranging from 42.5 to 14.5 per cent.

TABLE 3.
ANALYSES OF PHOSPHIDES.

Mineral.	Ni.	Fe.	P.	Meteorite.
Rhabdite	42.5	41.5	15	Beaconsfield Cranbourne No. 1
	38	49	13	
Schreibersite	29	56	13	Cranbourne No. 1
	22	70	7	Cranbourne No. 2
	22	..	8.5	Cranbourne No. 2
	18	66	14	Beaconsfield
	20	67.5	13	Cranbourne No. 1
Yellow phosphide	14.5	69.5	16	Cranbourne No. 1

This probably accounts for most of the variation in the phosphides. At the same time, it seems probable that there are two series of phosphides, one of which contains about only half as much phosphorus as is found in the more common varieties. It seems possible that this may be the fourth variety—schreibersite B—described above.

Oxidation Products.—Many of the fragments of scale removed from the meteorite consist of numerous unreplaced remnants of nickel-iron up to 3 mm. in diameter, cemented together by ramifying limonite. Sometimes even larger plates of iron were preserved. Such fragments generally have a hackly fracture and, when polished, simulate an iron-limonite breccia. Other pieces of the scale are sheet-like or lens-shaped, and consist essentially of limonite showing well-shaped colloform banding. The limonite is studded with minute prisms and rhombs of rhabdite, much in the manner of the original iron. No trace of the schreibersite B veins was observed, and in view of the ready attack of HCl on this mineral it is thought that the presence of lawrencite in the meteorite could be held accountable for this.

Trevorite.—Intercalated with the limonite bands are bands of a pinkish-brown mineral, which appears to have formed along either side of the open cracks. It is an isotropic mineral which is inert to all etching reagents but hot HCl, and is hard, but can be dug out with a micro-drill. The powder so obtained is distinctly magnetic, and yields positive microchemical tests for both iron and nickel. It is regarded, therefore, as trevorite, and resembles the trevorite found by Stillwell (7) in the Caroline meteorite.

Chlorides.—In places the scale is coated with minute pustules of yellow and green substances. The yellow material sometimes appears first as liquid drops, darkens on exposure, and turns dark-brown in a few days. Some of it was quite soft at first, but became sticky after exposure for a period. Microchemical tests showed that this material consists of ferric chloride, indicating that it is *lawrencite*.

The green encrustations have the colour of a nickel salt, and microchemical tests proved the presence in them of nickel and chlorine, with a trace of iron. The iron was probably derived from attached limonite, so that the encrustations probably consist of nickel chloride.

Acknowledgments.

In conclusion, we wish to thank Mr. W. Baragwanath, Director of the Geological Survey of Victoria, for permission to examine the meteorite. Much helpful information concerning its occurrence and history was received from Mr. D. J. Mahony, Director of the National Museum, and the late Mr. W. Abrahams, Curator of the Geological Survey Museum.

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Explanation of Plates.

PLATE II.

- FIG. 1.—End on view of the Pakenham meteorite, showing Widmanstätten structure on the polished surface, which has been etched with 2 per cent. HNO_3 in alcohol. The oblique lighting makes the taenite appear as dark lamellae. Actually these dark bands are composite, consisting of thin parallel lamellae of taenite interleaved with kamacite as shown in Fig. 5. An unusually large area of schreibersite B occurs near the right-hand edge of the polished surface. Its shape is largely controlled by the octahedral structure of the iron. (Magnification: one-half.) (J. S. Mann, photo.)
- FIG. 2.—Polished section through the centre of a large pyrrhotite nodule. The irregular dark core consists of fine-grained pyrrhotite; the light zone around this consists of graphite and pyrrhotite intergrown, with a narrow dark marginal zone of clean pyrrhotite. Enclosing this is a narrow rim of limonite and iron-nickel phosphides. The phosphides appear white. (J. S. Mann, photo.)

PLATE III.

- FIG. 3.—Shows the typical occurrence of rhodite as small rhombs and prisms in the kamacite, after etching with 2 per cent. picric acid in alcohol. ($\times 150$.)
- FIG. 4.—Typical rhombs of rhodite in kamacite, etched as above. ($\times 660$.)
- FIG. 5.—A typical dark band of the Widmanstätten structure shown in Fig. 1, revealing its composite character. Thin parallel lamellae of taenite, with characteristic saw-tooth margins, occur interleaved with bands of kamacite. The small clear area interrupting one taenite lamella (top right) consists of phosphide. Etched as above. ($\times 150$.)
- FIG. 6.—Parallel lamellae of taenite in kamacite. On the left is a typical vein-like occurrence of schreibersite B along the grain boundary between kamacite grains. Its brittleness makes it difficult to polish, and gives it a characteristically fractured and pitted surface. Etched as above. ($\times 100$.)
- FIG. 7.—Portion of an iron-nickel phosphide rim enclosing a pyrrhotite nodule. The white areas are schreibersite. The gray area (with scratches) separating the schreibersite areas consist of the softer creamy-yellow phosphide. ($\times 80$.)
- FIG. 8.—Minute lenticular bodies of (?) daubreelite forming parallel strings in a single pyrrhotite grain. Etched with saturated KOH. The same nodule as in Fig. 7. ($\times 400$.)



